Fabrication and testing of a large active primary reflector structure

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ABSTRACT

This paper discusses the fabrication considerations and propose.d testing concepts for a twelve meter, graphite-epoxy space truss that is being developed to provide structural support for the primary mirror system of the SpacE Laser ENErgy (SELENE) Beam Transmission Optical System (BTOS). A general description of the mirror support configur at ion is presented. Specific issues which are addressed include low-cost fabrication techniques utilized in the support structure. Later, a description of the dynamic testing program for the entire active primary mirror system is outlined.

2, INTRODUCTION

BTOS is a portion of a larger project, SELENE, which is managed by NASA's Marshall Space Flight Center and utilizes a high energy, free electron laser to transfer energy from the ground to orbiting spacecraft or other customers such as lunar colonies. BTOS is the system that transmits the beam energy from the laser to the target. BTOS receives a one meter diameter power beam which has a Strehl ratio of 0.9 or greater. The BTOS project is under the cognizance of the Jet Propulsion Laboratory and provides the. adaptive optics, pointing, and tracking subsystems.

To satisfy requirements for the SELENE project, which include a Strehl ratio at the receiver greater than 0.5, it is necessary for the beam to correct for atmospheric disturbances.[1] Atmospheric correction for the BTOS project is accomplished through the usage of an active primary mirror. 'I'o achieve the necessary correction, the initial design for the primary mirror system requires the usage of over 150,000 hexagonal, 3 cm flat-to-flat mirror segments, each of which arc capable of being commanded at over 300117. in tip, tilt, and piston by utilizing three voice coil act uators.[2]

Due to the challenging control requirements, the project felt it was necessary to determine early in the program if dynamic interaction between the control system and the mirror segments, mirror support panels, and primary mirror support structure would be a problem. Once evaluated, efforts could then be concentrated on solving any troublesome dynamics issues prior to proceeding with the remainder of the. project. The effects of dynamic interaction can be simulated in computer models when all the structural components are characterized to the same level of fidelity. Unfortunately, the spatial scales involved in BTOS run the gamut from 3 cm sizes operating at 300+ cycles per second to 1200 cm sizes vibrating at 5- 10 cycles per second. As an example, the first few frequencies of the support structure will be under 10 Hz, however, knowledge of the dynamic mode shapes is needed up to 300 Hz. Typically, only the first ten or twenty modes of a structure are predictable with a finite element model. To get the accurate mode shapes at 300 Hz would require that the 100th or higher modes be accurate, which is never the case. It was decided that a testing program be developed that would answer the questions related to dynamic interaction. One portion of that test program will involve dynamic testing of a selected number of mirror support panels mounted 10 a full size primary mirror support structure. It was further decided that a structure 12 meters in size must be made along with representative mirror segments and mirror support panels, in order to determine whether or not dynamic interaction problems would exist, For cost saving.. potential, a major goal of the test support structure was to be built with the correct geometry and materials so as to become the first operational support structure. The first portion of this paper discusses the design and fabrication issues of the large primary mirror support structure. The tatter portion of this paper discusses the dynamic testing program for the entire active primary mirror system.

Design and fabrication issues for the hexagonal, twelve meter flat-to-flat, graphite-epoxy primary mirror support structure must be dealt with simultaneously. Minimizing cost without sacrificing performance was a major goal for the BTOS primary mirror design, The basic structural design was established by considering deflection requirements caused by gravity and thermal conditions, and producing tight, non-slip joints. Once the basic structural design of a tetrahedral spacetruss was adopted, considerations for a low overall fabrication cost became the primary driver for the detailed design. Cost was broken down into piece-part procurement costs and assembly costs.

Testing of the primary mirror structure will focus on characterization of the basic primary mirror support truss and dynamic interaction with the active components of the primary mirror. Different facets of the testing program will address control loop problems related to various spatial frequencies and the need for passive damping of the cluster panels. This multi-faceted testing program will identify potential problems in the BTOS primary mirror system, and will attempt to correct them. Successful testing of this structure will enable the BTOS project to proceed with confidence into the next design phase, which includes a complete prototype system.

3. DESIGN AND FABRICATION CONSIDERATIONS

The design for the BTOS primary mirror support structure must consider many issues, Figure 1 shows the conceptual design configuration developed in an earlier study phase.[5] Concerns related to performance. of the optical system have priority over all other concerns. Strength issues are important as well because BTOS is integrated and operated in the presence of environmental conditions such as gravity, thermal gradients, and atmospheric turbulence. Concerns related to fabrication and assembly costs helped to finalize the prototype design.

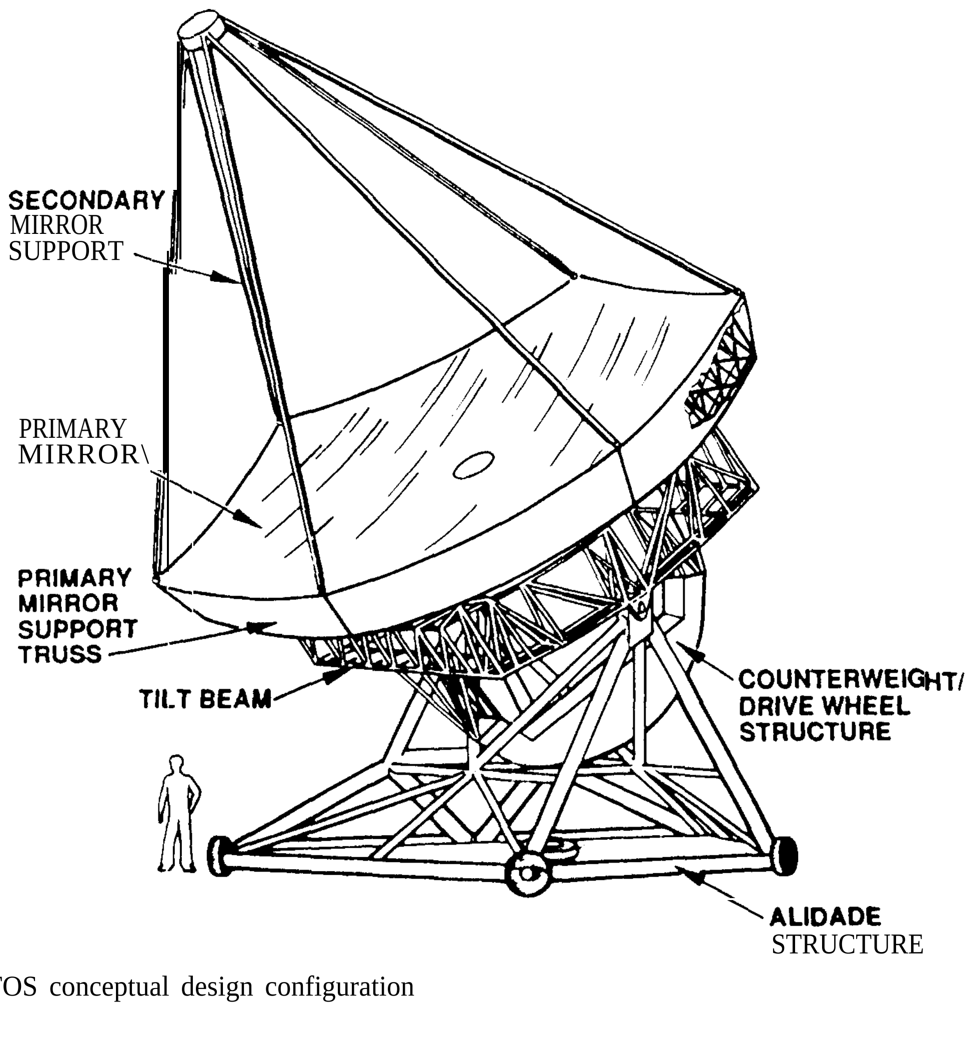

Figure 1, BTOS conceptual design configuration

3.1 Design considerations

Many assumptions were made because the overall BTOS system has not been finalized. The design issues which led to the prototype design were documented in an earlier paper.[3] A summary of the major design issues focused on the following three considerations.

The first consideration involved the stiffness of the support structure. Frequency requirements have not been established for the primary support structure, however, the conceptual design had a fundamental frequency of the primary/secondary support at 6.8 hertz. The static deflections associated with the conceptual design were determined to be reasonable, therefore the new design must meet or exceed a fundamental frequency of 6.8 hertz.

The second consideration was with regards to thermal performance. The figure of the entire primary mirror must be held well within the ranges of compensation for the mirror segment actuators during all temperature ranges. The cur rent design for the mirror segment assemblies also required that the small gaps between segments must be tightly controlled due to the sensitivity of the edge sensors. TO compensate for large thermal (or gravity) motions normal to the surface, a separate metrology system (a measurement system with commanded actuators) will be needed. To minimize radial and tangential deformations due to temperature variations, it was felt that a passive system should be used, as opposed to a costly three degree-of-freedom actuator system. To this end, the design for the primary mirror support structure itself must minimize in-plane motion due to thermal extremes and gradients.

The third consideration was the requirement to survive gravity loads and other environmental loads such as turbulence caused by the atmospheric conditioners or earthquakes. Wind loads were assumed to bc negligible. due to the presence. of an enclosed dome. For safety reasons, a factor of safety of 3.0 on gravity loading was self-imposed on the design to account for these effects.

3.2 Fabrication considerations

A highly regular design was invoked to allow for mass production techniques. Assembly costs were lowered by employing simple tooling fixtures to assemble and drill the graphite-epoxy tube struts. Overall cost for assembling the entire truss was reduced by minimizing the need for special purpose tooling, while maintaining the required precision of the finished truss.

Early in the design phase for the primary mirror support truss, cost was identified as a major concern. Steps leading to the final design dealt with issues such as a simple regular design, minimizing the number of elements, simplified assembly procedures, and low procurement costs for piece parts.

The preliminary design work done in 1992 lacked simplicity in the primary mirror support truss design. The design work done favored an arrangement of struts that featured a symmetric top chord system but forced the bottom chord arrangement to be complex. Also the number of struts for that design included more than 1300 tube assemblies with five different cross-sectional areas. Upon revisiting this arrangement, a greatly simplified design was developed, as described in the next section,

Assembly costs can often times be greater than the piece part costs of individual components. For this reason, special attention must be given to the method of assembly, The elimination, or simplification, of tooling can save money directly, if a satisfactory method of producing a reasonable quality part can be found. By automating the assembly procedure at the individual subassembly level, a great deal of assembly time can be saved.

Drilling holes in the field can be extremely expensive. Assuring high quality of the holes with regards to tolerances could be impractical. By pre-drilling holes in a controlled environment, the quality of the subassembly can be ensured, while at the same time giving the crew which assembles the entire structure a head start towards final alignment.

Finally, accepting the fact that a finished interface can be carefully controlled through the use of variable thickness shims, allows the remainder of the structure to be built with larger tolerances during the assembly process.

Also, a design which allows for small tolerance errors will help minimize the amount of rework during the assembly process. This type of joint must be capable of resisting the loads without slippage.

4. PRIMARY MIRROR SUPPORT CONFIGURATION

This section presents the results of a few months of concentrated effort to develop a detailed design of the primary mirror support truss system for the BTOS structure. All of the issues and concerns mentioned above were taken into account when deciding the prototype design, Once analyses were completed, layouts were produced. It was at this stage of the design that the complex issues of fabrication, including piece parts, subassemblies, and final assembly, were worked to their conclusions. The results of these efforts arc documented in the ten released production drawings which are needed to fabricate the entire primary mirror support truss. Marshall Space Flight Center has undertaken the task of procuring all piece parts and assembling the truss, Production of the composite tubes has begun, with completion of the entire primary mirror support truss expected in late 1994.

4.1 Design of support truss

Early in the detailed design phase, it became apparent that if the number of mirror support panels was decreased, that the total number of tube assemblies could be decreased, By increasing the size of the panels from 1.0 meter flat-to-flat to 1.3 meters flat-to-flat, and by improving the arrangement of the panels, the number of panels decreased from 136 odd-shaped panels to 90 hexagonal panels. This led to a decrease in the quantity of tube assemblies from over 1300 to 789 tube assemblies.

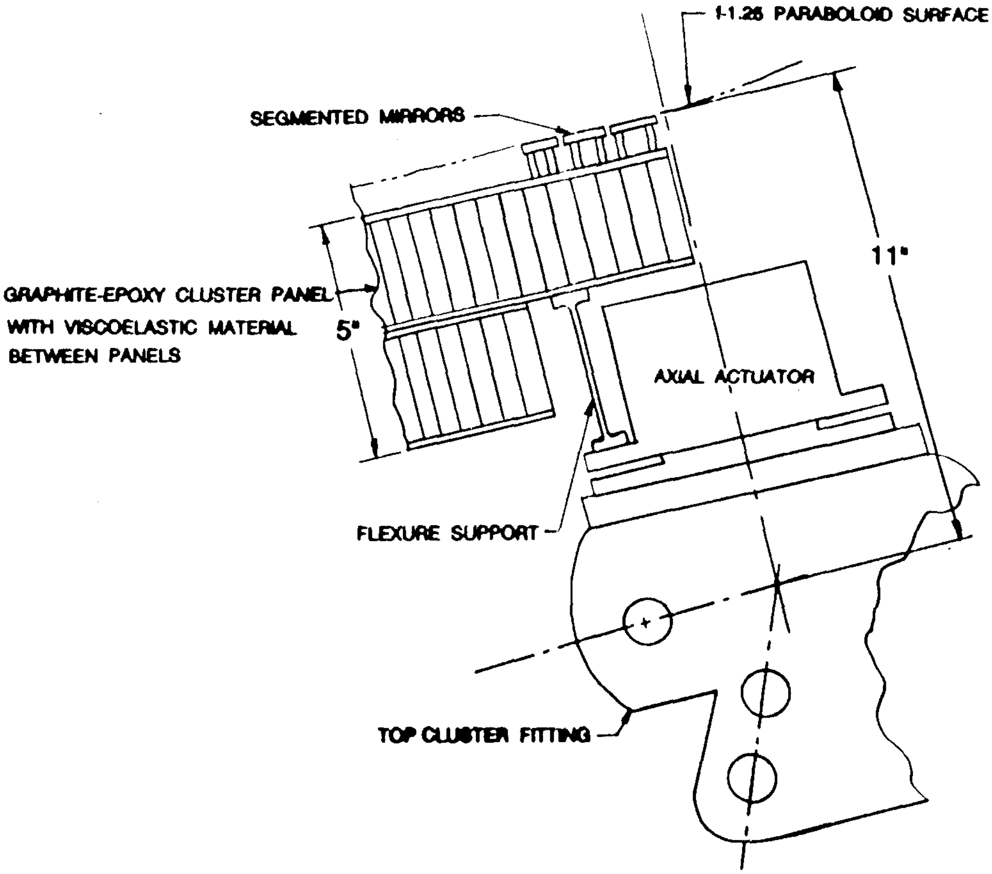

Figure 2. Relative locations of mirror segments, cluster panels, and support truss

After assuming certain thicknesses for the mirror segments and the composite mirror support panel, a set of intersect ion points were created that became the centerlines for all intersecting tubes at each joint. Figure 2 shows the relat ionship between the mirror segments, cluster panels, and support truss structures. A space of 11.00 inches was chosen, knowing that this value could be achieved using off-the-shelf actuators for the metrology system. Once the first intersection point was established, all other intersection points were instantly known because from the top view, all intersection points lined up to form perfect isosceles triangles. The height of the intersection points (relative to the central vertex) was established by maintaining an 11.00 inch offset normal to the true parabolic surface of the primary mirror segments. The lengths of the top and bottom tube assemblies vary by small amounts to account for the changes in angles. The depth of the truss remained nearly constant, because the bottom surface was formed by projecting the top surface down by 60 inches. Therefore the lengths of the diagonal tube assemblies are similar.

4.2 Tube production

Once the geometry was established, a finite element model was developed to determine the necessary cross-sections of the tubes. To help reduce the costs incurred with utilizing large numbers of cross-sectional areas, the entire truss was assumed to only have three different cross-sections. The initial selections which met the frequency goals arc 3.00" outer diameter with .1OW wall, 3.00" outer diameter with .150" wall, and 3.00" outer diameter with .300" wall. Section 4.2 discusses the preliminary analyses. Based on cost considerations and thermal performance, it was felt that the material of choice was a pultruded graphite composite for the tube with bonded stainless steel end fittings. A value of 17.3 x 10^6 psi was estimated for the elastic stiffness of the tube. The tube fiber layup consists of Hercules AS4 Carbon filaments with a vinylester matrix. The fibers are nearly all unidirectional. A matted fiber layer is co-cured on both the outside diameter and inside diameter to facilitate handling and fabrication loads. These layers account for less than 10% of the cross-sectional area. The tube has 62% fibers by volume. The vinylester resin was chosen over an epoxy matrix because it has a longer period of stable viscosity (3 to 5 days versus 6 to 12 hours) and has greater shrinkage which aids in mold release.' To further reduce costs, the thinnest wall thickness (.100") was deleted and replaced with the .150 wall thickness to reduce the number of production run setups required by the manufacturer. The entire batch of over 4000 linear feet of tubing was pultruded and initially cut in two days. Cutting of the. tubes to precise lengths was done in a separate operation.

4.3 End fitting preduction

The method of production for the end fittings became clear when the quantities of end fittings was known. Since all the outer diameters of the tubes were identical, all the fittings could also be identical. The exception to this is that the top ends of all the diagonal tube assemblies and some of the top chord tube assemblies required a double bolt connection to resist some moderate bending moments. A total of 300 double bolt end fittings and 1278 single bolt fittings are needed for the finished assembly, Casting the 15-5PH stainless steel fitting.., heat treated to H1150, and using them essentially in the as-cast condition was considered to be the lowest cost approach. An inexpensive finish machine cut of the inner diameter of the tube socket was the only machining required. After the end fittings were bonded to the t ubc using epoxy, the holes were then precision drilled to a highly accurate (+/- 0.001") center-to-center length. The holes were. standard drill sizes for a 3/4' diameter bolt. Due to the large size of the fastener, the estimated preload in the joint will provide enough frictional resistance to prevent slippage of the part during telescope operation,

4.4 Cluster fitting producticm

The design of the cluster fittings was much more complicated. Because the top fittings provided the interface to the 90 mirror support panels, the top face had to be cut at a precise angle which was normal to the paraboloid surface. This led to 36 different fitting designs. However, the attachment of the nine tube assemblies was very repetitive except for small changes in the position of the bolt holes. The common design features of the cluster fittings demanded that a casting process be employed, Casting individual fittings with different top plate angles would be cost prohibitive. To allow for the benefit of casting the basic features and maintain the 36 different designs, it was decided that welding a cap plate to a machined casting was the most cost effective method of production. After many methods were discussed, the method outlined below was arrived at for finishing the 198 individual cluster fittings All the top cluster fittings and four of the bottom cluster fittings required the welded cap plate. The remaining 86 bottom fittings did not require a cap plate. The steps which led to the finished machined cluster fittings arc outlined below:

a) Inspcct and deburr the castings (108 top and 90 bottom).
b) Machine bottom surface flat and pcrpcndicular to vertical axis.
c) Machine top of fitting to desired angle.
d) Weld 6.00" diameter lascr cut cap plates to top surface.
c) Heat treat part to HI 150.
f) Finish cut top surface and drill a centering hole.
g) Secure part to a "rotisserie" tool. Precision drill hole.s in each of the nine flanges.
h) Dcburr and clean.

4,5 Final assembly

Final assembly of the structure is anticipated to be rather simple. Since all the holes arc pre-drilled in the cluster fitting and all the center-to-center tube lengths arc prccision engineered, the amount of time spent fine tuning the structure will be negligible. The tube assemblies and cluster fittings will be initially assembled with very low torques applied to the bolts. At selected intervals of the assembly, precision measurements of the top surface will be made using thcolodite triangularization to determine deviations from the desired paraboloid shape. Once the tops arc in position, the final high torque values will be applied to the. bolts. Disassembly and reassembly of the entire truss will bc required for shipment to various testing and operational sites. Only a limited number of joints will need to bc disassembled.

4.6 Structural analyses

To aid in achieving the optimal design for the primary mirror truss, a MSC/NASTRAN model was dcvclopcd. Figure 3 shows a plot of the finitc clcmcnt model. It accurately re.presented the individual tube assemblies and lumped the mass of the 12,087 pound mirror/mirror support panels into 108 locations. The assumed configuration of the secondary mirror support structure was also included. A total of 908 elements and 322 grids were utilized. To simplify the analysis, it was assumed that the alidade structure and tilt beam structure were rigid. The connection to the tilt beam structure is expected to be free to *move* radially, constrained in tangcntial and axial motion, and pinned in the three rotational degrees of freedom at each of the four interfaces. Analysis shows that the design has a fundamental frequency of 7.7 hertz which basically corresponds to the secondary mirror moving side-to-side causing the primary mirror support structure to "potato chip". Some selected modes are listed below

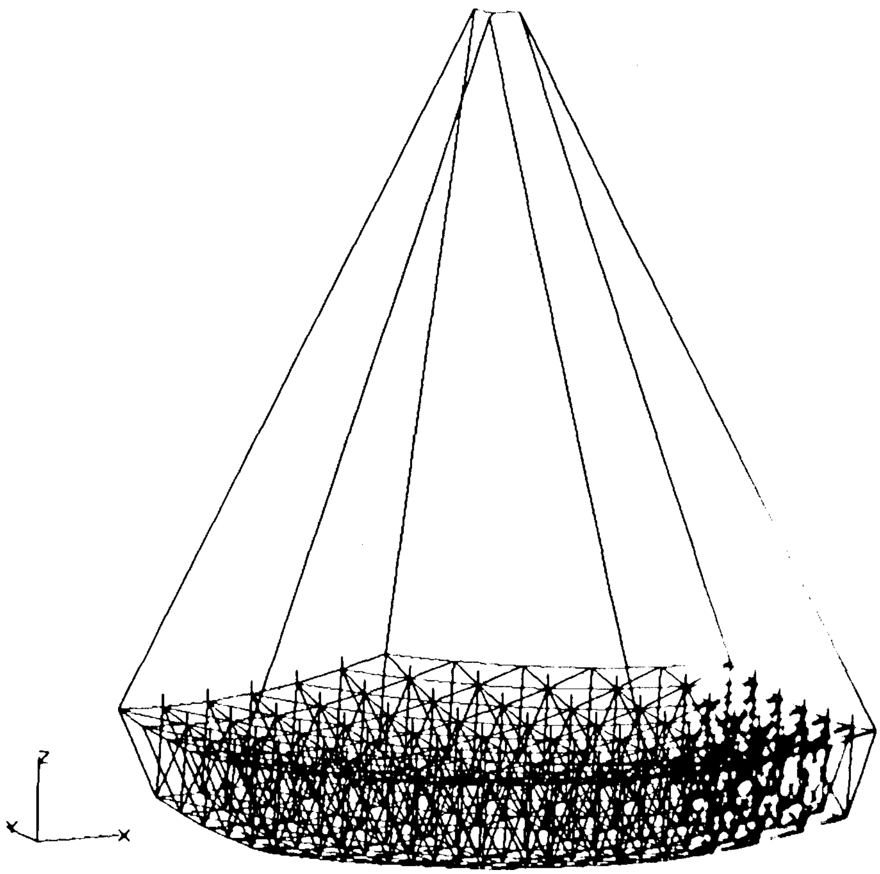

Figure 3. Plot of primary and secondary mirror support finite element model

Mode	Frequency	Description
1	7.71 Hz	Secondary + X/+ Y motion with Primary support potato chipping
2	7.88 Hz	Secondary + X/-Y motion with Primary support potato chipping
3	8.21 Hz	Secondary twisting about” Z axis
4	9.31 Hz	Secondary twisting about Z axis with some lateral motion
6	9.67 Hz	Secondary support beams bending in weak axis
10	13.09 Hz	Secondary support beams strong axis with Primary support tubes near the six corners exhibiting strain
13	16.36 Hz	Primary support potato chipping with secondary mirror X motion
15	20.42 Hz	Primary support potato chipping with secondary beams exhibiting complex bending in weak axis

The highest stresses for the assembly occur in the bond between the end fittings and the tube. The highest stress in the bond is estimated to be 1295 psi. This assumes a factor of safety of 3.0 and, given a conservative epoxy bond allowable strength of 1800 psi, gives a margin of safety of 0.38, which is adequate. Stresses in the steel end fittings are low (23,500 psi) and stresses in the cluster fittings are higher at 84,000 psi but are still within the allowable of 105,000 psi for the 15-5 PH H1 150 stainless steel, It should be noted that after the analysis was completed, a design change to eliminate the smallest cross-section tube (.100” wall) and replace it with the medium size tube (.150 wall) was done in order to save costs for production of the tubes. This will produce a small increase in the overall stiffness of the support truss.

5. DYNAMIC TESTING PLAN

The plan outlined in this section was derived from a preliminary draft of a comprehensive plan developed in 1993.[5] A brief introduction to the problem of dynamic instability is described, followed by the testing objectives, testing approach, completion criteria, and a brief description of individual proposed tests, The test plan includes testing of many elements of the BTOS system which have not been discussed in this paper, namely, the mirror segments and the mirror cluster support panels. These items are being developed by Marshall Space Flight Center and are still in the initial development phase. Notwithstanding, a comprehensive test plan is required to answer the questions related to all aspects of the dynamic instability issue.

5.1 Background on dynamic instability

The BTOS system will introduce a compensating phase distortion to the outgoing high power laser wavefront by properly positioning small 3 cm hexagonal mirror segments of the primary reflector at a bandwidth of approximately 300 hertz. As the primary reflector support structure is expected to have frequencies below 10 Hz and the cluster panel structural resonances will be at approximately 100 Hz, possible deleterious interactions between the wavefront control system and the telescope structure are of great concern.

To see how an adverse interaction can occur, suppose a particular segment, segment i, is commanded to move away from the support structure. The corresponding reaction force will drive the support structure in the opposite direction, launching a wave of deformation throughout the structure. Suppose further that the requirement for segment i to move in the commanded direction was influenced by the position of some other segment, segment j, which itself had moved away from the support structure; that is segment i is tracking segment j. If the deformation wave reaches segment j with a phase angle that exacerbates the segment-to-segment tracking error, a runaway dynamic instability will occur.

In a sense, destabilizing control-structure interaction (CSI) is an artifact of modeling error. Indeed, if the structure and the control system, including the actuators and edge sensors, could be accurately modeled, the control dynamics could in principle be designed to achieve the desired performance goals without incurring CSI risk, in the example given above, the error is caused in controlling the segments as if the structure were a rigid body, when in fact the support structure is flexible, A second way modelling error can lead to dynamic instability is by allowing deleterious interactions between various control loops; this can be referred to as destabilizing control-control interactions (CCI). The baseline BTOS aperture is approximately 12 meters in diameter. To achieve a good correction of atmospheric distortion, the wavefront corrector segments must be roughly the size of an atmospheric seeing cell which, for light with a wavelength of 0.85 urn, is approximately 3 cm at 70 degrees from zenith, Thus, the BTOS primary reflector will be comprised of over 150,000 segments, each of which is controlled in three degrees of freedom: piston, tip, and tilt. These roughly 0.5 million control system degrees of freedom provide ample opportunity for modeling error to produce unstable CCI.

Obviously the key to avoiding both CSI and CCI is accurate modeling. There arc, however, practical limits to how accurately both the structure and the control system components can be modeled. With respect to the structure, it is well known that finite clement methods provide mode frequency and mode shape predictions whose accuracy degrades with increasing frequency. Moreover, standard finite clement methods do not predict structural damping characteristics. In practice, only the first few low frequency modal characteristics arc believable (to an accuracy of 10% to 20’%), and structural damping estimates are inserted into the model based on experience from similar structures or actual test data. Control component modeling accuracy is generally limited by availability and computational resources. It would be impractical to include detailed models of each of over 1 million control components in a design model, even if such detailed models were believable.

To mitigate these difficulties, tests will be carried out on a full scale dynamics test article. The article will consist of the prototype support structure supporting dynamically correct reflector segments controlled by representative servo loops. These tests are designed to yield more complete analytical models, to identify the nature and extent of any deleterious dynamic interactions, and, if necessary, to assess the efficacy of various dynamic interaction suppression measures (e.g., structural damping treatments).

5.2 Objectives of the testing program

The four principle objectives of the BTOS control dynamics test program are first to gain confidence that the BTOS support truss can achieve the performance required for the SELENE project. Secondly, characterize the support structure in the range of frequencies most critical to CSI and CCI. As excessive control loop phase lag near the gain crossover frequencies is a dominant issue, this frequency range must be beyond 300 hertz. The characteristics to be determined include mode frequencies, mode shapes, and modal damping. Third, investigate the nature and scope of both CSI and CCI instabilities by monitoring excursions of the BTOS elements from their expected positions. If unstable interactions are experienced, tests will be conducted to identify and characterize the offending source. Finally, if deleterious dynamic interactions are discovered, evaluate the effectiveness and practicability of various suppression measures. The measures include passive constrained layer structural damping (cluster panels, truss elements or both), active struts (controlled as tuned dampers), proof mass actuators (controlled as energy sinks), phase stabilizing control compensators (lead filters), notch filters (phase loeked loops), and adaptive control (direct or observe.r based).

5.3 Approach to testing

The testing will be performed on a full scale support structure designed to the load requirements of an actual BTOS telescope. The intention is that, baring unforeseen circumstances, the test article could function as the support structure for the prototype SELENE system.

Testing will be performed in phases, with each phase building in complexity. The outcome of each phase will be an incremental improvement to the overall system model, which will be verified in subsequent phases. Early testing will focus on characterizing individual structural elements and assemblies, These will be followed by modal tests on the fully integrated test article. Testing will then shift toward control dynamics, with isolated panel testing done first followed by integrated system testing, and finally interaction suppression testing as required.

To minimize cost, the full 12 meter aperture will be populated with only a limited number of representative BTOS cluster panels and actuated mirror elements. It is envisioned that only three cluster panels will be necessary to characterize the entire structure by mounting a pair of adjacent reference panels in one location on the aperture, and selectively mounting the third BTOS panel into different locations throughout the aperture for each test. The pair of panels could be moved to different locations as well. Rigid dummy masses would be mounted to the top cluster fittings at all other locations to effectively mass load the structure and thereby maintain the correct support truss dynamics.

A second cost cutting measure is to reduce the number of actuated elements. The motion of individual 3 cm mirror segments would be simulated by a few larger actuated masses (simulated mirror groups or SMG's) which would represent the collective motion of 300-400 individual mirror segments. It is felt that the coupled motion of the rigid SMG would present a more severe dynamic interaction problem to the support structure than the potentially decoupled motion of the individual 300-400 mirror segments. By reducing the number of actuated elements, one can also reduce the number of edge sensors, measurement locations, and control software complexity.

A third cost cutting measure is to avoid construction of an optically complete telescope. Thus, there will be no secondary mirror, secondary mirror support, wavefront source or wavefront sensor. The SMG's would not be required to support optically reflecting surfaces except what may be required as part of the test measurement system, The SMG control loops will be designed to be dynamically representative with respect to CSI and CCI, given that such optical components are absent.

5.4 Completion criteria for testing

In general, the performance of a typical control system will improve with increasing bandwidth until either the sensor noise limit is reached, internal amplifiers saturate, or a dynamic instability is encountered. Assuming that the amplifiers are designed with the proper dynamic range for the application, a drop in performance is a telltale indication of the onset of instability. In its most obvious form, dynamic instability in a control system manifests itself either as an uncontrollable resonance or a runaway swing to actuator physical stops,

The test program will be considered complete when it has been demonstrated through a combination of testing and testing based analytical extrapolations to the BTOS operational configuration that CSI and CCI instabilities either do not exist or can be effectively suppressed through the application of one or more stabilization measures. The presence. or absence of instability will be judged on the basis of control system performance degradation as the bandwidth is increased from O hertz to the required 300 hertz. Stability will be declared if 300 hertz is reached without a noticeable drop in performance, where noticeable is defined with respect to the BTOS operating wavelength of 0.85 um.

5.5 Proposed test outline

The task of determining the critical interactions between components of a system with the complexity of SELENE is an immense undertaking. To render the problem tractable, it is necessary to subdivide the testing problem into smaller parts. These smaller parts must be chosen to provide meaningful results that are scalable to full system performance. The sub-scale tests must capture enough of the essential behavior of the full scale system that they expose all important problems. The manner in which the tests scale to the full scale performance must be understood in detail,

The plan outlined below is expected to evolve as the components become available and results from preliminary phases of testing become known. The phases of testing are component testing, integrated testing, and follow-up testing.

The detailed plan (not shown) includes analysis specific to each testing step. The objectives of this analysis are:

1) to ensure that the test procedures will yield useful results, 2) to provide predictions of performance for each test as a benchmark against which results can be measured, and 3) to determine quantitatively how test results scale to system level performance.

For each test, the detailed plan will define the basic test goal and then will:
a) identify the required a priori analytical work and background information,
b) specify the test configuration,
c) specify the facility needs,
d) define the software requirements,
e) define the instrumentation/measurement needs,
f) briefly identify the test procedures, and
g) identify potential follow-up analytical work.

5.6 Component testing

Truss Tube Modal Test

Determine the elastic stiffness, modes, frequencies, and structural damping of an individual structural tube. Perform test on at least two different tube assemblies. Verify stiffness by taking strain data during an axial pull test. Measure modes, frequencies and damping during a sinusoidal vibration test.

Cluster Panel Modal Test

Determine the modes, frequencies, and structural damping for a BTOS cluster panel mounted on BTOS flexures, but supported on a rigid test frame. This test would be performed on potentially more than one design of a panel. Damping could be improved greatly with the use of a constrained layer system. Proper selection of the final panel design hinges on this test, Measure mode.s, frequencies, and structural damping during a sinusoidal vibration test.

Support Truss Static Test

Determine stability of support truss when subjected to large external forces. This test attempts to determine the capability of the bolted joints to resist sliding forces. Large static (or potentially dynamic) forces must be induced to check the stability of the joints. Measurements can be made before and after testing.

Support Truss Modal Test (unloaded)

Determine the modes, frequencies, and structural damping for the support truss without mass simulators. Utilizing approximately 250 accelerometers, reasonably accurate modes, frequencies, and structural damping characteristics can be determined, Use of 50 pound shakers can effectively excite the structure.

Support Truss Modal Test (loaded)

Determine the modes, frequencies, and structural damping for the support truss with all mass simulators in place. Utilizing approximately 250 accelerometers, reasonably accurate modes, frequencies, and structural damping characteristics can be determined. Use of SO pound shakers can effectively excite the structure. Attempt to identify the first 25 modes and frequencies.

SMG Control Functional Test

Confirm functionality and stability of the control software/hardware with regards to a small number of simulated mirror groups (SMG's) mounted to a rigid plate. Apply various dynamic inputs to individual SMG plates, multiple SMG plates, and the rigid plate itself to determine the response characteristics of the SMG system,

5.7 Integrated testing

Cluster Panel/Support Truss Modal Test

Determine the modes, frequencies, and structural damping for a BTOS cluster panel mounted on BTOS flexures, but mounted to the BTOS support truss. Compare the results of this test with results from the cluster panel modal test.

SMG/Cluster Panel Control-Structure Interaction Test
Determine the basic characteristics of the control software/hardware with regards to a small number of SMG's mounted to a BTOS cluster panel on a fixed base. Repeat the tests performed in SMG control functional test and compare results. The. differences in results are directly related to the presence of the cluster panel, and this information can be quantified,

SMG/Cluster Panel/Support Truss Control-Structure interaction Test
Determine the basic characteristics of the control software/hardware including SMG'S mounted to a single BTOS cluster panel on the support truss. Repeat the tests performed in the SMG/cluster panel control-structure interaction test and compare results. The differences in results are directly related to the presence of the support truss, and this can be quantified, Additionally, external sources of vibration can be applied to various points on the support truss.

Multiple Panel Performance Test
Determine the basic characteristics of the control software/hardware with regards to SMG'S mounted to multiple BTOS cluster panels on a support truss. The tests performed above can be repeated to help gain insight into the behavior of the entire flexible support truss. This is the test of the whole system, and as such, many tests will need to be performed to gain a comprehensive understanding of the system, The measurement system required for this set of tests is much more complex than in any previous test, because the relative motions between activated components is occurring over a far greater distance than before. One scenario for measurement is to use a set of lasers mounted high above the support truss which reflect light from carefully positioned retroreflectors for translation measurement and flat mirrors for rotations mounted to the surface of the SMG's. Since the paired cluster panels will remain in the same location for many tests, the laser measurement system can remain freed. The third panel, however, will be moved from location to location, thereby requiring the laser system to be realigned for each test. One laser system will be needed for each actuated panel or other target.

5.8 Follow-up testing

Due to the unknown events that will arise during component and integrated testing, it is difficult to anticipate the scope of follow-up testing, As a minimum, it is anticipated that as new hardware (i.e. segments, edge sensors, actuators, etc.) or software are developed, additional testing on the BTOS test article will be necessary. Although it is easy to overlook this phase of testing, it may prove to be the most valuable, and as such, the schedule, test personnel, and financial resources must be budgeted to carry out this final phase of testing and bring the testing program to its successful conclusion. It is anticipated that the entire testing program could be completed in under two years.

6. SUMMARY

The primary mirror support truss for the BTOS project has been designed with many issues taken into consideration, The design first addressed strength, temperature, and dynamic requirements. The concerns for low cost production required that the design pay special attention to reducing complexity, minimizing labor intensive steps, and taking advantage of repetitive piece part production. The results of complete structural analysis and many detailed discussions with the assembly, material, and fabrication groups are documented in the form of released production drawings. Production of the composite tubes has begun, with completion of the entire primary mirror support truss expected in late 1994.

Testing of the support truss can commence once the prototype article has been assembled and shipped to JPL. In anticipation of the arrival of the test article, a detailed, comprehensive plan has been formulated to adequately quantify whether or not there are any CSI or CCI instability issues relative to the interactions between the BTOS support truss, cluster panels, or mirror segments, The foundation of the test program has been established

7. ACKNOWLEDGEMENTS

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